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INFRASOUND, ITS SOURCES AND ITS EFFECTS ON MAN

AEROSPACE MEDICAL RESEARCH LABORATORY,
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

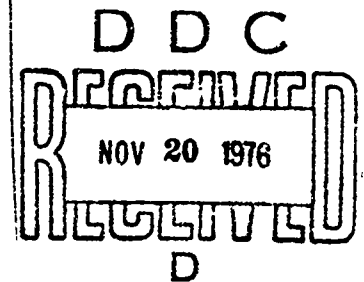
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Infrasound, sinusoidal pressure variations from 0.1 to 20 hz, is somewhat more complicated to measure and analyze than sound of higher frequency. But the most common error in analyzing infrasound is not to also measure the higher frequency sounds and then interpret these sounds with respect to their effects on humans. Generally, where there is intense infrasound, there are also intense sounds above 20 Hz; and these are the sounds that cause adverse human effects. At sufficient intensity infrasound is audible, but is easily masked by higher frequency sound. Infrasound does not often occur at levels that are harmful or even audible to man. Thus infrasound exposure is not one of mankind's more pressing environmental problems.			

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SUMMARY

Infrasound, sinusoidal pressure variations from 0.1 to 20 Hz, is somewhat more complicated to measure and analyze than sound of higher frequency. But the most common error in analyzing infrasound is not to also measure the higher frequency sounds and then interpret these sounds with respect to their effects on humans. In most cases where there is intense infrasounds, there are also intense sounds above 20 Hz and it is these sounds that cause adverse human effects. At sufficient intensity infrasound is audible, but is easily masked by higher frequency sound. In general, infrasound does not often occur at levels that are harmful or even audible to man and for this reason exposure to infrasound is not one of mankind's more pressing environmental problems.

INTRODUCTION

The definition of infrasound that will be used in this paper is the sinusoidal pressure variations between 0.1 to 20 Hz. This definition, proposed and accepted in 1973 at an international colloquium on infrasound, is not accepted by all scientific disciplines. For example atmospheric scientists use the term infrasound to describe any slow periodic atmospheric pressure change and thus normal changes in barometric pressure would be considered infrasonic. The measurement techniques, as well as the auditory and physiological effects on man, for pressure variations from 1 to 20 Hz are different than the techniques and effects for slow (<0.1 Hz) pressure changes. Therefore the reader of any article on infrasound is cautioned to make sure of the frequency range being described.

This paper will be organized into five sections: Infrasound Measurement, Infrasound Sources, Auditory and Physiological Effects, Infrasound and Vibration, and Annoyance. Possible ways of reducing the effect of infrasound will be discussed throughout the paper.

INFRASOUND MEASUREMENT

In general, the techniques required to measure audible sound are appropriate for measuring infrasound. The key consideration is the low frequency response of the microphone. The low frequency limit of a microphone using a diaphragm is controlled by the time constant of the pressure equalization hole connecting the rear of the diaphragm to the atmosphere. Without

such an equalization hole, the ideal microphone will measure static pressure. However, most microphones are not ideal and charge leakage in capacitor or piezoelectric microphones also serve to limit low frequency response. For most infrasound measurements, a low frequency cutoff below 0.1 Hz is desirable in any case since large static pressure changes could substantially affect the performance of the measurement system. Commercial measurement systems provide good response down to 0.01 Hz. Of just as great importance is the high frequency response of the measurement system. Measurement of infrasound without measurement of the audible frequencies has led to many unwarranted conclusions about the effects of infrasound on man. The upper frequency limit of the measurement system should be at least 1000 Hz and preferably 10,000 Hz. Calibration can be accomplished by a pistonphone, although at low frequencies an error as large as 3 dB can occur due to heat loss to the walls of the pistonphone.

The analysis of infrasound is in many respects more difficult than higher frequency sounds. There are no weighting curves such as the A-weighting curve for which to combine frequencies. Frequency modulated tape recordings become essential for detailed analysis and from these recordings a narrow band spectral analysis can be performed. Such analysis takes considerable time due to the low frequencies of the signal.

The alternative that is often almost as informative is to use an oscillograph for the low frequencies below 10 Hz and a regular spectral analysis above 10 Hz. The information of practical importance can often be easily derived in this manner.

INFRASOUND SOURCES

As seen in Table 1, infrasound occurs as the result of a variety of events in nature as well as certain man-made systems. Infrasound occurs naturally due to fluctuating wind, air turbulence, volcanic activity, ocean waves etc. Natural activities of a person such as jogging, walking, sitting up or lying down, etc., must in themselves cause infrasonic exposure to that person. For example, running in a way that causes the head to vary 15 cm in altitude causes an exposure to a sound pressure level of approximately 90 dB (re 20 micro pascals). Swimming in such a way that the ear becomes submerged in

7.5 cm water during part of the stroke is equivalent to 140 dB. The reader can certainly think of other situations (such as elevators) that cause similar exposures. The point that I would like to stress is that the exposures from such natural activities apparently do not cause any adverse effects, which is just as well since there is no practical way to control or reduce such exposures. In almost all cases, however, such natural exposures are of a frequency 2 Hz or less.

Nature			Man-Made		
Source	Est Freq	Est Max SPL	Source	Est Freq	Est Max SPL
Thunder			Free Field		
Earthquake			Jet Engines	1-20	135
Ocean Waves	<1		Helicopters	1-20	115
Wind: 100 Km/hr		135 dB	Large Rockets	1-20	150
25 Km/hr		110 dB	Diesel Engines	10-20	110
Atmospheric Pressure			Activities		
Fluctuations	<1	100 dB	Running	<2	90
Volcano			Swimming	<2	140
			Riding in		
			Aircraft	<10	120
			Submarines	5-20	140
			Rockets	1-20	140
			Automobiles	1-20	120
			Helicopters	5-20	130

Table 1. Summary of some infrasonic sources (from ref. 4)

Man-made devices are also a significant source of infrasound as can be seen from Table 1. As opposed to natural occurring infrasound, the frequency tends to be more in the 2-20 Hz range. The largest exposures occur to persons riding in modern conveyances. The most typical source is the automobile. At highway speeds and with only one window open, natural resonances occur inside the car that have been measured as high as 120 dB at 15-20 Hz^{5,6,7}. The highest freefield exposures occur near jet aircraft (120 to 130 dB at 10 to 20 Hz) and the Saturn rocket (up to 145 dB near the launch pad, flat spectrum). The greatest infrasound exposure to men that I am aware of has been the result of fractured fighter aircraft canopies due to birdstrike. Sound Pressure levels of approximately 170 to 175 dB at 20 Hz have been recorded for several seconds under such conditions.

Infrasound penetrates walls and other such conventional sound insulation with considerably less attenuation than higher frequency sounds. Earplugs, for example, perform poorly with respect to attenuating infrasound at the ear. Earplugs, on the other hand, do provide some protection from infrasound. This is partly due to the good seal against air leaks. Prevention of air leaks thru structures is one good way to attenuate infrasound, but unfortunately this is not possible for most practical structures.

For this reason reduction of man-made infrasound is best accomplished by proper redesign of the infrasound source. Such redesign might consist of changing the operating conditions of machinery so that there are no natural resonances in the infrasonic range. However, I would caution the reader that shifting a problem from the infrasonic range to the low frequency range (20-100 Hz) will normally create a more adverse problem. As will be discussed later, for the same sound pressure level, low frequency noise affects man much more adversely than infrasound. Furthermore, it should be clear that for many sources, such as the Saturn rocket, no reduction is possible at all.

AUDITORY AND PHYSIOLOGICAL EFFECTS

A most common misconception about infrasound is that it cannot be heard. A glance at the results of various investigations^{9,10,11}, summarized in Figure 1 shows that infrasound can be heard (at least down to 1 Hz). Single frequencies of infrasound are not perceived as pure tones. Instead they are described as more of a chugging or motorboating sound. This leads one to the conclusion that what a person really hears is not a pure tone of infrasound, but instead the harmonics generated by the distortion from the middle and inner ear.

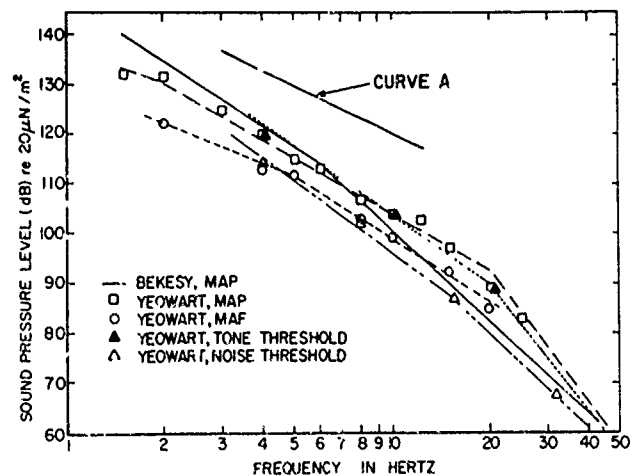


Figure 1. Hearing threshold levels for Minimum Audible Pressure (MAP), Minimum Audible Field (MAF) and for bands of noise. Curve A depicts the threshold of audibility due to middle ear distortion.

In our laboratory, we have tried to investigate the possibility of known non-linearities of the middle ear causing infrasound to generate audible distortion. From just the middle ear non-linearities described by Kobrak¹², we can predict that infrasound should be audible by the time the levels reach the curve labeled A in Figure 1. Now if the audibility of infrasound is due to harmonic distortion, then it should be possible to mask the harmonics that

are above 20 Hz. This is indeed the case. For instance a 7 Hz tone of 120 dB was easily masked in 5 out of 5 subjects if a 110 dB background noise (10-100 Hz) was presented¹³. A 10 Hz tone at 123 dB was detected by 6 subjects when it was added to the background noise shown in Figure 2. Often when analysing noise in general, noise control engineers have blamed some bizarre effects on infrasound just because narrow band analysis showed that the highest Sound Pressure Level (SPL) was a narrow band in the infrasound region. The point that I want to make here, is that for most noises that I'm aware of, it is not the infrasound that causes problems such as annoyance, chest vibration, etc., but audible frequencies above 20 Hz that are present in the noise.

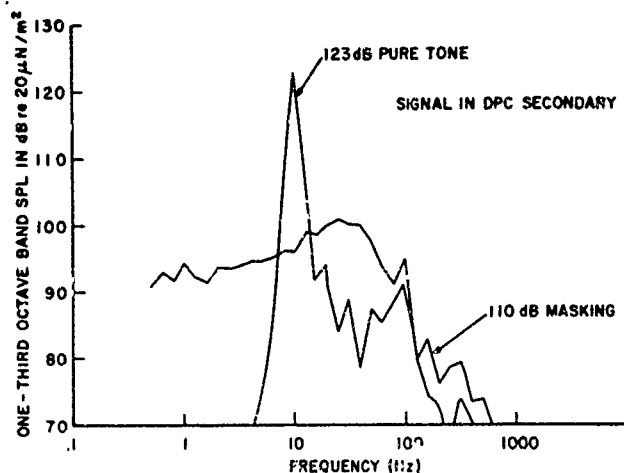


Figure 2. An overlay of both the one-third octave band analysis of a 110 dB background noise and a 123 dB 10 Hz tone. Only about one-half of the subjects could sense a difference between the combination of these noises and the background noise alone.

Another adverse effect of infrasound is the possibility of damage to the hearing organ. For exposures above 140 dB, Temporary Threshold Shift (TTS) of the audiometric frequencies above 125 Hz has been observed⁴, although the frequencies above 1000 Hz seem to be the most sensitive. The TTS observed was usually small (less than 10 dB) and recovered rapidly. Figure 3 is a summary of results of various exposures to infrasound and the resulting TTS⁴.

There is also the possibility of middle ear damage due to very intense infrasound. At 172 dB, exposures of 1 Hz (60 min), 4 Hz (15 min) and 8 Hz (7.5 min) all produced perforations of the tympanic membrane in chinchillas while exposures to 160 dB did not⁴. There have been exposures of the auditory system in humans as high as 172 dB for less than 30 sec (1-8 Hz), 160 dB for 1 min (8 Hz) and 155 dB for several minutes (7 Hz). For these short times, no damage to the tympanic membrane or middle ear system occurred. On the other hand Tonndorf reported scarring of the tympanic membrane of German submariners¹⁴. The exposure of men on

snorkel subs constituted quite high infrasound exposures for long time periods. Unfortunately, the exact exposure level received by the men is unknown except that it is estimated to be considerably above 120 dB. From these studies, however, it seems fairly clear that the middle ear is the most susceptible part of the body and that the physiological tolerance limit to infrasound is probably determined by the middle ear. When we look at pain, we see that it is related to mechanical displacement of the middle ear system beyond its mechanical limits. Thresholds for pain as determined by Bekesy and the Benox report¹⁵ are summarized in Figure 4. There is some deviation in the data, but for the most part this depends on the type of stimulus used and interpretation of the sensations identified: the pain threshold, tickle threshold, or the touch threshold. Nevertheless, the pain threshold is probably the best indicator that we know at this time as to the physiological tolerance limit.

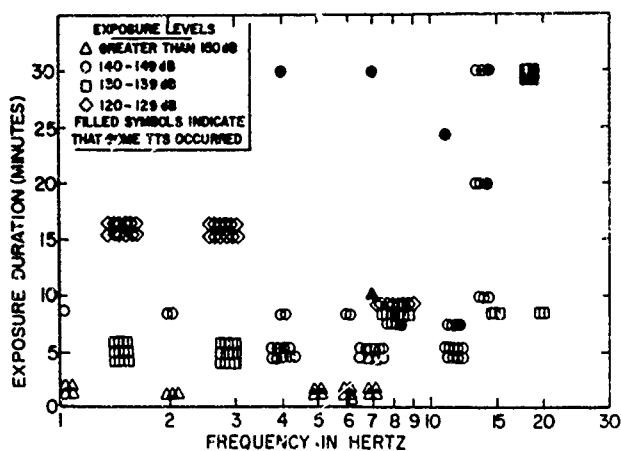


Figure 3. Conventional display of individual exposures recorded in our laboratory in terms of frequency and duration with levels as the parameter. Solid symbols indicate that some TTS was observed; the vast majority of exposures show no TTS.

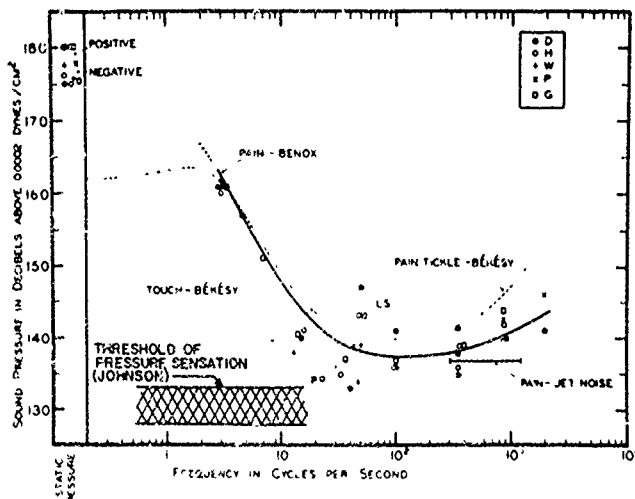


Figure 4. Thresholds of pain, tickle and pressure sensations.

Also in Figure 4 is a range of the threshold of pressure buildup due to whole body exposures. This pressure sensation in the middle ear first starts from about 127 to 133 dB and is one of the most consistent findings in our infrasound exposures with humans^{13,15,16}. The sensation does not necessarily become more intense as the SPL is raised and has been relieved temporarily by valsalva^{13,17}. This pressure sensation can be explained in terms of a rectification effect caused by the eustachian tube and differs little from what one would feel during a 50 or 100 meter altitude change¹⁸.

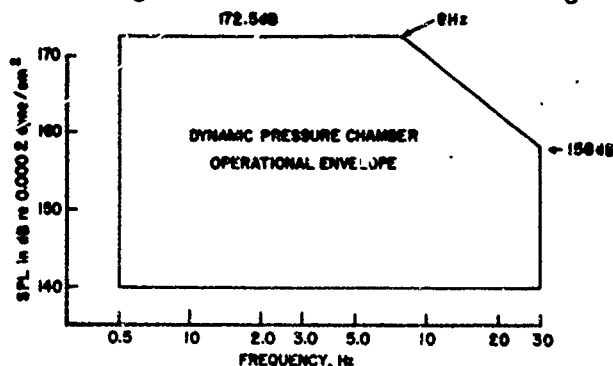


Figure 5. Operational Envelope of the Infrasound Source at the Aerospace Medical Research Laboratory.

To back up the statement that whole body exposure to infrasound (at least at levels up to 172 dB) does not cause non-auditory effects, a baboon, a monkey and six dogs of various sizes have been exposed, both with and without anesthesia, to infrasound levels at the operational limit of our infrasound producing equipment (see Figure 5). The awake animals did not exhibit any observable evidence that they were in any way adversely effected¹⁸. The animals remained calm and became excited only if changes in the exposure conditions were not accomplished gradually. With the anesthetized animals, there was no change in EEG or respiration rate until a SPL of 166 dB was reached. At this point respiration decreased until at 172 dB it normally ceased for the larger dogs^{18,19}. Figures 6 and 7 show the respiration of a 22 kilogram dog. The chest impedance measured the

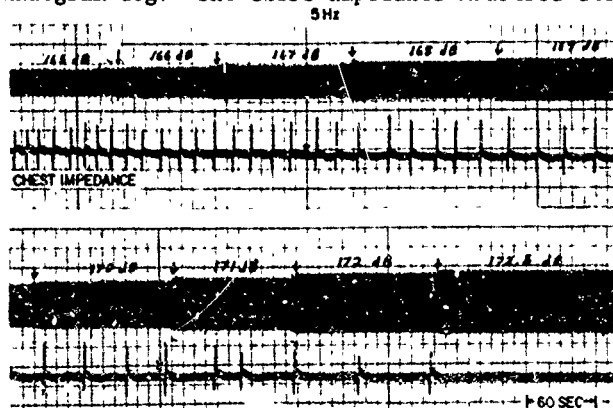


Figure 6. The effect on respiration of an anesthetized dog of slowly increasing the whole body infrasound exposure from 165 dB to 172.5 dB. The chest impedance correlates with chest motion. 12-4

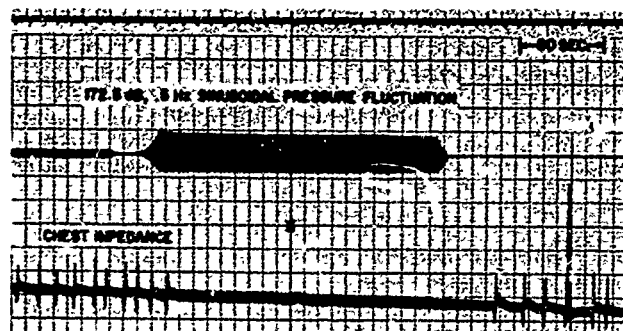


Figure 7. The effect on respiration of an anesthetized dog of a 3 1/2 minute exposure to 172.5 dB at 0.5 Hz.

movement of the lungs and it can be seen that for 172 dB, respiration stopped. The explanation of this phenomenon is that air molecules are being exchanged between the ambient air and the lungs of the dog since each pressure fluctuation causes a density change of 10%. Thus infrasound at 172 dB serves to ventilate artificially the dog's lungs. The frequency range for which I have found this effect is 0.5 Hz to 8 Hz, and it is interesting to note that below 1 Hz the chest is virtually motionless. I want to interject into my discussion at this time a picture of the device which I use to produce these pressures. It is called the Dynamic Pressure Chamber (DPC) and as seen in Figure 8, is quite a large and sophisticated device; but this is what it takes to produce a pressure variation that is more than one-tenth of an atmosphere (172 dB). Thus the discussion of such large pressures, and such respiration effects as I have just described, is largely academic as such exposures would be impractical even if one desired to cause them.

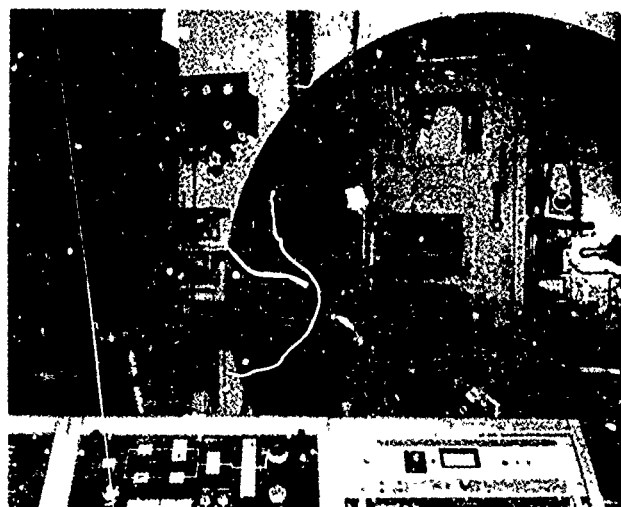


Figure 8. A picture of the infrasound source (called the Dynamic Pressure Chamber) used in the various experimentation at the Aerospace Medical Research Laboratory.

With respect to these high infrasound levels and possible physiological damage, one final experiment was performed. One dog was exposed over 6 weeks to more than a total of 14 hours

of infrasound at the operational limit of the DPC.¹⁸ The animal was then sacrificed and examined. No evidence of any pathological change was found. Thus in summary, the only clear physiological damage that does occur at even unrealistically high levels has been to the ear.

Besides direct physiological damage, there are many non-auditory effects possible. One of the first studies accomplished by our laboratory was a short range program to confirm that 140 dB would not jeopardize the mission of the crew of Apollo rocket.¹⁷ In this study various types of spectra and levels were used as summarized in Figure 9. In the infrasonic range, exposures of four experienced human subjects to discrete frequencies of as high as 151-153 dB were obtained for as long as 90 seconds.¹⁷ At these

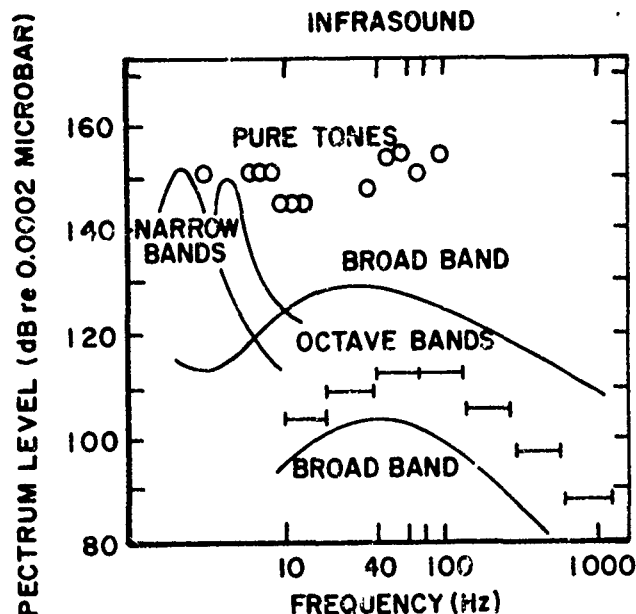


Figure 9. Representative Low Frequency and Infrasonic Test Exposures (adapted from Mohr, et al).

levels the subjects could feel the abdominal wall and chest wall moving. These sensations increased above 145 dB and at the 150-153 range the limit of voluntary tolerance was reached for the low frequency (above 20 Hz) exposures. This was due to the subject reporting a tickling and choking sensation in the throat, which led to the coughing response. One subject also reported mild nausea. The cause of this coughing reaction is most certainly the result of the oscillating air movement in the throat due to the pressure fluctuation. This air is undoubtedly drying the mucous membrane in this area, leading to tickling and choking sensations. In the animal experiments, the relative humidity was quite high and for this reason the drying effect was probably not predominating. Simple performance tasks were not affected by the infrasound exposures. The results of this early study¹⁷ are summarized in Figure 10. It is fairly evident that exposures to high intensity noises above 30 Hz are far more serious than

exposures to the infrasound range.

TOLERANCE DATA

EXPOSURE	OBSERVED BEHAVIOR
0-20 Hz 140 to 150 dB	No objective effects Exposures well within Tolerance. Middle ear Pressure
20 to 50 Hz Up to 145 dB	Chest Wall Vibration, Gag Sensations, Respiratory Rhythm Changes, Post- Exposure Fatigue; Voluntary Tolerance Not Exceeded
50 to 100 Hz Up to 154 dB	Headache, Choking, Coughing, Visual Blurring and Fatigue; Voluntary Tolerance Limit Reached
Discrete Frequencies	Tolerance Limit Symptoms
1-7 Hz at 153 dB 8-10 Hz at 145 dB 10-40 Hz at 140 dB	No Objective Effects Gag Sensation In One Subject Subjective Sensations Increase Rapidly Above 145 dB
100 Hz at 153 dB	Mild Nausea, Giddiness, Sub Costal Discomfort, Cutaneous Flushing
60 Hz at 154 dB 73 Hz at 150 dB	Coughing, Severe Substernal Pressure Choking Respiration, Salivation, Pain on Swallowing, Giddiness.

Adapted from MOHR et al

Figure 10. Observed behavior during exposure to representative low frequency and infrasonic test exposures (adapted from Mohr, et al).

Almost 10 years later (late 1973), a series of human whole body exposures (4 subjects) were completed. The maximum exposures were 144 dB for 8 minutes.¹⁶ In these exposures, there were no changes in auditory acuity, respiration rate, pulse rate, and general condition of the eardrum. The consistent findings were middle ear buildup (above 126-132 dB), voice modulation (above 135 dB) and chest vibration (above 135 dB). There were other miscellaneous observations reported by the subjects, but there is no proof that these were more than just an occasional response of an individual that could result from confinement to a rather small chamber for the experiment. The one psychological response that might be of importance is the lack of concentration or sleepiness. While I believe this is probably an artifact, this drowsiness has also been reported in an experiment by Borredon.²⁰

Borredon exposed 42 young men to 7.5 Hz at 130 dB for 50 minutes. This exposure caused no adverse effects and the only statistically significant change out of many parameters measured was an insignificant (less than 1.5 mm Hg) increase in the minimum arterial blood pressure. Borredon did report that several of his subjects did feel drowsy after the infrasound exposure.

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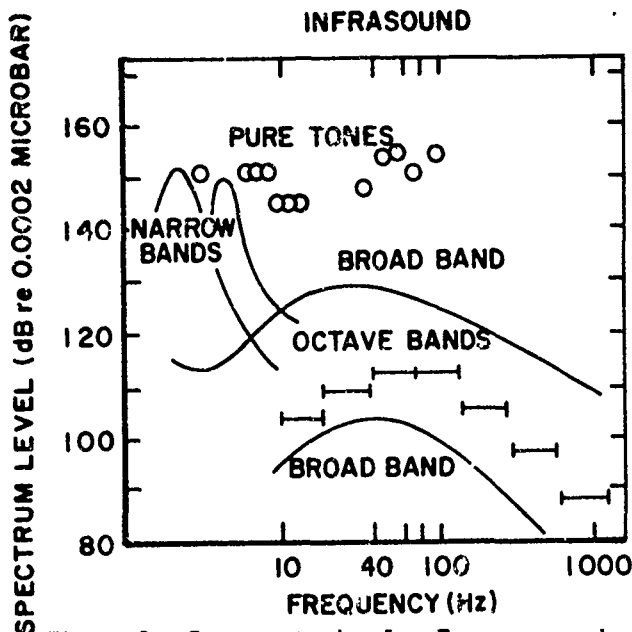


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inal mass, which moves in and out of the rib cage compressing the air in the lungs, that causes tolerance limiting resonance at 4-8 Hz²⁶. Infrasound, because of the long wave length versus body size, acts uniformly on the whole body, periodically compressing and rarefying the body. Displacement of tissue primarily occurs if air is displaced or compressed, and the main air enclosures of importance in the body are the lungs and the middle ear. Low frequency sound and infrasound will act simultaneously on the abdomen, chest walls, and mouth, all of which will affect the lungs. This uniform pressure will cause the system to act much stiffer than if the stimulus is unidirectional vibration. This is why the main thorax/abdominal resonances to sound are in the 40 to 60 Hz range²⁶. Such resonances have been measured by Leventhall²⁷ at Sound Pressure Levels as low as 105 dB, and if anyone sees the movie "Earthquake" (the Sound Pressure Level was measured as high as 120 dB in the 60-100 Hz region). The effect of such resonances are quite obvious. But I would emphasize that such resonances are in the low frequency range above 20 Hz, not in the infrasound range. This brings me to my last topic.

ANNOYANCE

Annoyance has been broken out as a separate topic because I believe that the greatest effect infrasound may have with respect to the general health and welfare is via all those many factors that make up the annoyance response. Now it is clear that if infrasound cannot be heard or sensed by a person, it should not annoy. Thus the threshold curves of Yeowart should serve as the threshold of any adverse infrasound effects on humans. Unfortunately, there are differences in the audibility of tones versus bands of noise as well as differences in Minimum Audible Pressure and Minimum Audible Field. Therefore, we might expect some variability as to what can and cannot be heard. Thus Figure 12 has a cross-hatched range in which the infrasound may first be audible.

To compound this problem, remember that we have found that infrasound can be easily masked by higher frequency sounds. Thus the threshold curve may not be applicable to many noises that have both infrasound and low frequency components. Furthermore, even though for some individuals, any infrasound that can be heard probably annoys, it does seem reasonable that for most of the population, the annoyance threshold would be greater. Since recently the U.S. Environmental Protection Agency has suggested an Ldn of about 55 dB as that value for audible sounds, the corresponding loudness curves for the Ldn of 55 dB should be appropriate to equate to the²¹ loudness of infrasound. Fortunately, Whittle²¹, et al have such curves

and the 45 phon curve (which is roughly approximate to an Ldn of 55) is estimated from their data. This is also drawn in Figure 12 for SPL's less than 120 dB. Note that there is relatively little difference between the threshold curves and the 45 phon equal loudness curve. This only illustrates the fact that unlike noises in the 100 to 1000 Hz range, the effects of infrasound can go from absolutely none to quite severe with relatively little change in Sound Pressure Level. There are other factors that limit exposure of an uncontrolled population to levels above 120 dB. The main consideration is with respect to the annoying rattling of buildings or even damage to such structures. It is interesting to note that around Cape Kennedy, 120 dB was used as the upper limit for short term exposures of people or communities around the large rocket launch sites²⁵. After over ten years of experience, this level seems to still be valid. Another reason for choosing 120 dB as the upper limit if the population is not to be adversely annoyed is the phenomenon of the middle ear pressure. The 120 dB value provides a 7 dB cushion against this disturbing phenomenon.

I do want to emphasize that I do not consider infrasound as a noise of an audible frequency that is amplitude modulated by an infrasonic frequency. For instance, the amplified beating of a heart or the pulsation of the helicopter is annoying, but if the audible sound above 20 Hz could be eliminated, I believe there would be no sensation to annoy at all.

One practical method for reducing the annoyance due to infrasound was first suggested by Gavreau²¹, and later Westin²⁹. Gavreau reported relief of the problems of infrasound was gained by masking the infrasound with high intensity sound such as music. This strategy certainly is in keeping with our limited experience. In fact, Figure 2 is a good example of such a strategy. Of course, care is required in order to insure the "cure is not worse than the bite."

CONCLUSIONS

The summary of various threshold levels where various physiological effects may take place is presented in Table 2. This table does not consider frequency and in that regard, the limits depicted in Figure 12 are probably more useful. In any case, this information should be used with caution. Actually, exposures to levels as high as these will be rare, and if such exposures do occur for any long period of time, it would be my advice to establish a short investigation to confirm whether or not adverse effects are occurring.

For lower levels of infrasound, I feel that annoyance is the main factor that dictates that

for uncontrolled populations, exposures that are either much above the audibility threshold or above 120 dB should be avoided.

SUMMARY

WHOLE BODY EFFECTS-----	Start noticing adverse subjective effects past 150 dB. Tolerance limit not reached. Middle Ear pressure buildup starts at 130 dB as well as voice communication modulation.
RESPIRATION-----	Definite effect once 166 dB is reached.
VESTIBULAR-----	No effect identified on human subjects at levels as high as 155 dB. Effect on animals does occur occasionally, but at very high sound pressure levels.
AUDITOR-----	A small amount of TTS has occurred for exposures longer than 20 minutes, but generally level below 150 dB is not expected to produce adverse results if the exposure duration is less than 30 min.

Table 2. Summary of the thresholds of where various effects are expected to occur.

In perspective, infrasound is far less of a problem than the audible frequencies, and in the extreme, remember that normal walking or jogging can cause an infrasound exposure of approximately 90 dB at 1 or 2 Hz due to the change in altitude. I don't think that anyone would claim that jogging is harmful to hearing. On the other hand, a 90 dB tone at 1000 Hz can damage hearing. For such reasons, infrasound exposure forms only a very small part of the problem mankind has with environmental noise.

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The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 80-33.

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